Chapter 3

Reconnection and compression experiment

Reconnection within magnetized plasma occurs when two separate regions of magnetic field come in contact in such a way that the magnetic fields of the two regions are oppositely directed in the vicinity of the interface surface (separatrix). A change of the topology of the magnetic field then occurs in which the separate field lines merge at the reconnection zone, and become a single larger field line that now connects the two regions. Reconnection of field lines in a conducting fluid is only possible if the field lines are able to diffuse relative to the fluid. However, due to the high conductivity of laboratory and astrophysical plasmas, classical resistive diffusion rates are far too slow to account for the incredibly rapid rates of field line merging observed in actual reconnection processes such as the tearing mode instability within tokamaks. To explain the anomalously fast diffusion rates that occur within the core of laboratory fusion plasmas, several theoretical models have been proposed.This chapter presents the results of a series of experiments that studied the interaction dynamics that occur when an accelerated compact toroid is injected into a solenoidal target magnetic field, which can be aligned either parallel or anti-parallel to the internal field of

CT at its leading edge. Depending on the alignment direction, MHD predicts that the interaction should result, respectively, in either compression or reconnection of the two fields. This effect has been studied using a fast framing camera that can take a sequence of 12 images of the SCT during the interaction. The images can be taken at rate of one frame every 2 μs or at one frame every $0.25\mu s$. Using these images, the spatial and temporal dependence of light emission intensity of the CT during the interaction is compared to its emission intensity without the external field. The framing camera data is consistent with the data taken on the same set of shots from surface magnetic probes, and laser interferometer measurements of plasma density.*Motivation and relevance to other experimental theoretical results, Questions about driven reconnection, Fast reconnection, resistive MHD. Current sheets Comparison to MRX, Swarthmore. What make this experiment unique.*

3.1 Experimental set-up

In these experiments four external magnetic field coils have been installed on the CTIX accelerator for the purpose of applying magnetic perturbations to CT within the accelerator region. The coils are solenoids concentric with the center axis of the accelerator that produce an axisymmetric B field that is directed along the axis of CTIX near the middle of the coils, but also has a radial component near the ends of the coils. Because the magnetic field produced by the coils is primarily directed axially, we refer to these coils as Axial Field Coils.The direction of the external magnetic field produced by these coils can be aligned either parallel or anti-parallel to the internal field of CT at its leading edge. Depending on the alignment direction, basic resistive MHD predicts that the interaction should result in reconnection of the two fields for the case of anti-parallel alignment, or a compression effect in the case of parallel alignment. These effects have been measured on CTIX using surface magnetic field probes, and a laser interferometer chord at the 142 cm position on the accelerator, and also by using a fast framing camera that images the plasma along an axial line of sight. High reproducibility and high rep-rate allow for a large set of high quality data, and the results

of the three independent diagnostics provide consistent and complementary new information about the reconnection physics within the SCT plasma.Axial field strength can be varied, Observables relevant to reconnection and compression Data sets, number of shots

3.2 Description of external coils

Four external axial field coils are installed on CTIX for the purpose of applying magnetic perturbations to the accelerating SCT. The coils are solenoids concentric with the center axis of the Accelerator, (the z-axis), and located at z = 65 cm, z=100cm, z = 120 cm, and z= 148cm, as measured from the start of the formation section to the start of each coil. Each coil has 25 turns of 2 cm diameter welding cable. Each coil is L cm long and inner diameter of A, and produce 1.85 Gauss per Amp at coil center.

Insulating acrylic support spools encircle the 16cm OD stainless steel pipe comprising the accelerator section of CTIX. The spools are suspended by an independent support structure that carries the weight of the coils and also maintains a 2 cm gap between the ID of the Acrylic spool and the OD of the SS pipe. This gap is needed because the Accelerator section is charged to high voltage (up to 15 kV) and can heat up to as high as 140 deg F as a result of repeatedly carrying high pulsed current loads (10 kA) during shot runs that can last many hours.

The welding cables have been wound around the spools to form the coils, and connected in series to a variable DC power supply. Each coil can be individually connected or disconnected from the circuit to produce a variety of field geometries. Only 3 of the coils were used for the reconnection/compression experiments, those being the coils at z= 100 cm, 120 cm and 148 cm. The coil at z= 65cm was disconnected because early tests indicated that it disrupted the CT formation process when run at high current.

3.3 Diagnostics

The CT location and field structure during the acceleration can be well characterized by surface magnetic field probes that measure the axial component B_z and toroidal component BT of the time dependent magnetic field at three different positions along the accelerator, at z = 57 cm, 91cm, and 142cm.

The closed magnetic structure of the CT results in a localized pulse in the B_z signals that propagates down the accelerator. Under normal operation probe signals show peak B_z fields that remain approximately constant as the CT is accelerated.

Our fast framing camera diagnostic uses an Imacon 790 tube to make 12 visible light images of the plasma during each shot. Each frame is 400 ns in exposure duration, with a time delay of 2 ms between frames. Visible light emission is primarily from impurities in the trailing plasma, and so the framing camera is able to image the plasma sheath in the transition region between the CT field and the purely toroidal field behind the CT that is caused by the rail-gun acceleration current.

The framing camera is well suited for measuring the level of angular variations in plasma density and current density in the CT, as an indicator of the quality of the equilibrium.

For the reconnection experiments the framing camera is very useful because it simultaneously provides a time history of the axial position of the CT, as well as the radial and angular variation in light emission.

Line of sight passes though glass windows and mirrors into an f 4 zoom lens, mounted onto the framing unit. The output phosphor plate is viewed by a 384×576 pixel CCD camera to make a digital image of the shot. Since only visible light can make it out of the vessel, and be imaged by the camera, the diagnostic ability of the framing camera is limited to only observing plasma processes which emit light in the visible.

This means that the CT itself, which is a hydrogen plasma with a high ionization fraction, is not directly observed by the framing camera, (or the spectrometer) since it emits most of its light

in the UV. The framing camera only observes emission by neutral hydrogen atoms, and impurities.

Since neutral atoms are not directly acted on by the accelerating fields they can not be co-moving with the CT given the very fast timescale on which the CT is accelerated and propagates the length of the accelerator.

Impurity ions are directly acted on by the accelerating E and B fields, but because of their larger mass to charge ratio, they are accelerated less than the protons and electron of the CT. This linear centrifuge effect causes the impurities to trail behind the CT, and do not persist within the CT. Thus the framing camera views a halo around the CT, and which can be used to infer CT itself.

The He Ne heterodyne laser interferometer measures the time evolution of line averaged electron density at the three diagnostic port positions on the accelerator.

3.4 Experimental Results for no Target Field

Magnetic field probe data. Probe signals show peak Bz fields that remain approximately constant as the CT is accelerated. Time of flight shows steady acceleration*Reference results of MHD equilibrium paper*

3.5 Results and analysis

Framing camera data. Observe diminished light from in front of center conductor Magnetic field data. Decrease in Peak Bz field as CT enters Axial field. Time of flight shows slight increase in rate of acceleration The toroidal component of B, or B_θ , is important part of the reconnection process. During reconnection, the BT component advances into the external field, ahead of the CT. The signature of the CT itself is a localized Bz component, and high density. The framing camera measures the brightness of the plasma as a function of position and time. We have compared the average of 20 images taken with no axial magnetic field to the average of 20 images taken when the CT is injected into an axial field of - 400 Gauss (in the anti-parallel direction). In the time-sequence

of images below, pixels colored Red show where the plasma was brighter without the axial field, and pixels colored Blue show where the plasma was brighter with the axial magnetic field turned on. For Black pixels there was no difference.We have also compared the average image taken with no axial magnetic field to the average image taken when the CT is injected into an axial field of + 400 Gauss (in the parallel direction). In the time-sequence of images below, pixels colored red show where the plasma was brighter without the axial field, and pixels colored blue showwhere the plasma was brighter with the axial magnetic field turned on. For black pixels there was no difference in plasma brightness.

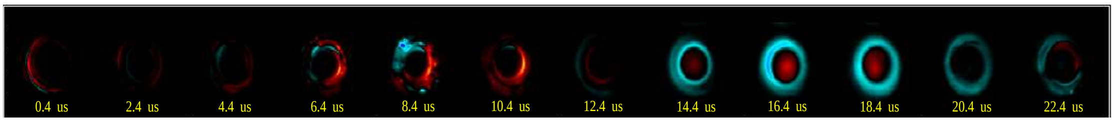

Figure 3.1: Compression effect of axial field on light emission from CT

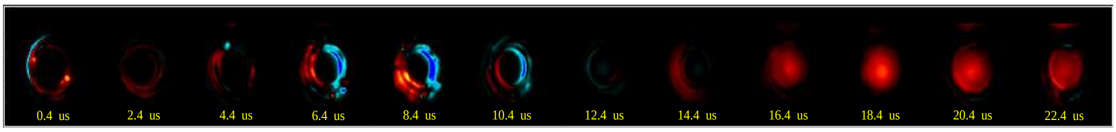

Figure 3.2: Effect of reconnection with axial field on light emission from CT

When the CT is fired into an anti-parallel magnetic field, we observe a decrease in light emission from the region in front of the center electrode, implying plasma is prevented from filling in this central region. Also we measure the internal field decrease and the CT velocity increase due to interaction with the anti-parallel field. These results are consistent with the effect of resistive MHD magnetic reconnection. Further quantitative analysis on the rate of reconnection are the next step with this project.When the CT is fired into a parallel magnetic field, we observe an increase in light emission from the region between the center electrode and the outer electrode, implying

plasma density and corresponding luminosity greatly increases before the CT is able to leave the accelerator section. We measure the CT velocity slow dramatically and the internal field increase due to interaction with the parallel external field. These results are consistent with the effect of MHD compression Interferometer data Results of Compression Study Magnetic field data. Increase in Peak Bz field as CT enters Axial field. Time of flight shows dramatic decrease in rate of acceleration (a=0)Interferometer data. Observe compression effect in increased line averaged electron density measured at z= 142 cm position. Density increase by a factor of 1.5 for B_{AF} = 400 Gauss Framing camera data: Observed increase of light emission from trailing plasma located in the accelerator section. This implies that trailing plasma is prevented from getting past the compression interaction region.

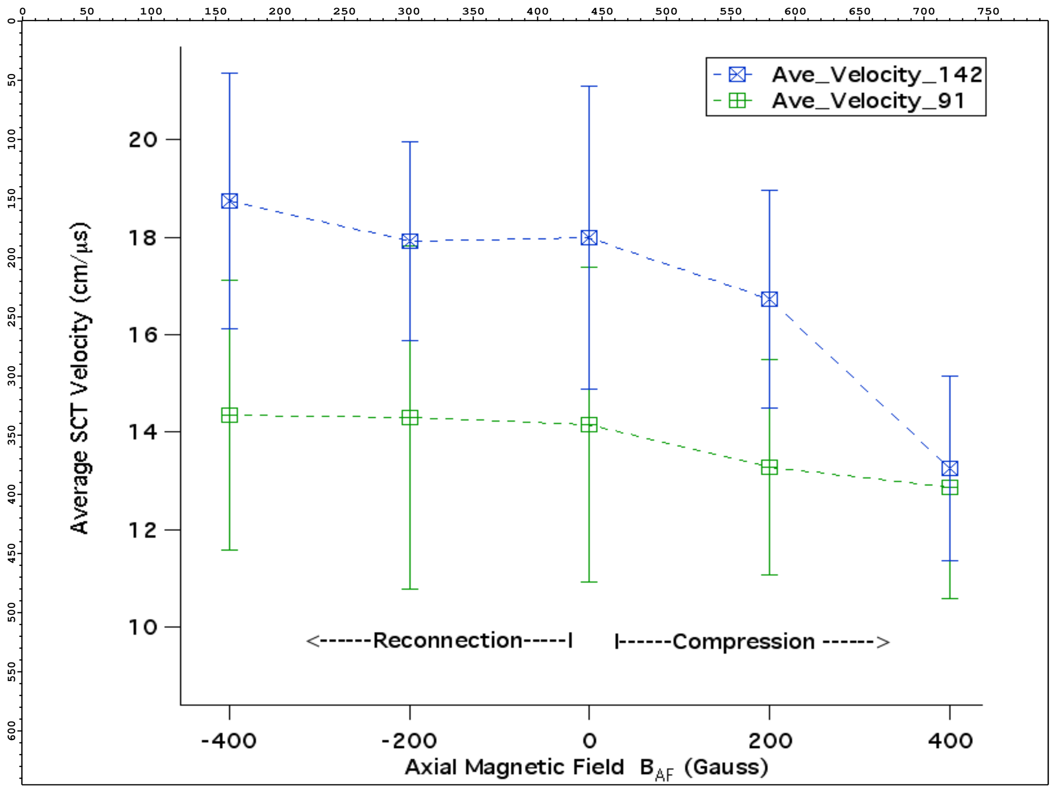

Figure 3.3: Effect of external field on CT velocity

After reconnection, the expected mechanism for plasma fill-in of the region in front of center conductor is Cross-field diffusion. Less plasma is seen in this region for $B_{AF} = -400G$ than for $B_{AF} = 0$For $B_{AF} = +400G$ most of CT plasma does not leave the end of the center conductor. During the compressional interaction its brightness increases due to the increase in density.

3.6 Model of System

CT field geometry.Axial field geometry.Axial field effects When the Compact Toroid enters an axially directed magnetic field, there is either an attractive force or a repulsive force of interaction between the two fields. This is just like two magnets being brought together along the axis of their poles. Whether the interaction is attractive or repulsive depends on the polarity of the external axial field relative to the internal field of the CT plasma. The magnetic polarity of the CT is fixed, as it is determined by the electrical polarity of the CT formation circuit and formation seed field, while the externally imposed magnetic field can be easily varied in polarity and strength for the sake of experiment. To understand and predict this qualitative effect of either attraction or repulsion, it is simplest to consider the poloidal component of the internal field (the component which is created by toroidal plasma currents), since its geometry is analogous to the field of a simple permanent magnet. In standard operation the CT is accelerated with the North end of its poloidal field at the leading edge, so that the poloidal magnetic field vector (near the center axis) points in the direction of motion, which we call the positive z direction. Then if we were to apply, via a solenoid, an external axial field with its North pole pointing backward toward the oncoming CT, we would expect the two fields to repel each other (North repels North). With the addition of this repulsion force, the CT would accelerate less than normal or it may even decelerate as it enters the target solenoid if the field is strong enough. On the other hand, if we had oriented the external field so that its South pole was facing the CT's North pole as it approached, then we could confidently predict that the CT will be attracted toward the external solenoid (South attracts North). In this configuration the

linear acceleration of the CT will be enhanced above the normal value caused by the rail gun circuit alone. While this simple intuitive model of magnets attracting or repelling one another is correct on a basic level, and does predict the approximate outcome of actual experiments, it leaves out many important and complicating subtleties.The first detail that must be considered is that a compact toroid is a plasma, not a rigid body. It is a conducting fluid with a nearly frozen-in magnetic field, and is capable of compression or expansion. When the CT is accelerated into a repulsive target field we would expect that the CT will be compressed in the z direction since it is being pushed on from both ends, from behind by the pushing field of the accelerator and in front by the repulsive axial field. The CT density and internal field will increase until some sort of pressure balance is reached. Although this compression is relatively straightforward, there are some interesting effects that are possible. Radial variation of the external field can provide a weak spot for the CT to squeeze through. If the external field is high enough reflection of the CT may occur.A very different process occurs when the CT is propelled into an attractive field. In that case, the full complexity of the plasma shows itself during the process of magnetic reconnection. This is a topological change in the structure of the magnetic field in which effective rate of diffusion of magnetic field lines relative to fluid elements typically exceed what would be expected based on the bulk resistivity of the plasma. The two separate magnetic fields merge as the outermost field lines of the compact toroid reconnect with adjacent field lines of the external field; each pair of closed lines becomes a single longer field line that encircles the still distinct inner field lines that have yet to reconnect. This is accompanied by (or mediated by) a layer of strong electric current at the surface of reconnection. The key condition for reconnection is that the magnetic field change sign in at least one component as the surface of interaction is crossed. The second detail is the actual geometry of the internal and external magnetic fields and the boundary conditions that the conducting walls of the vessel apply to the plasma and fields.Reconnection plays a critical role in the dynamo formation process of the CT, it limits the acceleration timescale, and is important when considering injection/refueling into a tokamak type reactor.Produced several new findings about the phenomenon of magnetic reconnection

in the presence of fast plasma flow:Reconnection rate is more than an order of magnitude faster than resistive magnetic diffusion rate, and is comparable to Alfven velocity of SCT.Reconnective flux cancellation effect, and SCT kinetic energy gain during reconnection, is proportional to the external axial field strength.Framing camera images have demonstrated the efficient trapping of SCT plasma on the external field lines, and have provided information about the radial dependence of reconnection effects. Measured magnetic compression effects that occur when the SCT is injected into an axial magnetic field. Increase of plasma density by a factor of 1.5 for a target axial field of 400 G , as observed by interferometer data.Increase of peak SCT Bz field strength of 60% as SCT enters axial field of 400 G, as observed by magnetic probe data.Increase of plasma light emission consistent with density increase, as observed by fast framing camera images.

Reconnection Results As the CT enters an axial field that is aligned anti-parallel to the internal field of the CT we observe three main effects with the magnetic probes. First, we observe a significant decrease in the peak value of the Bz field as it propagates into the axial field. This is consistent with magnetic flux cancellation that should occur within the reconnection zone. The amount of reconnective flux cancellation that is observed in our experiment is directly proportional to the strength of the applied external field, with the initial CT field strength being held constant. Secondly, we observe an increase in the acceleration of the CT that is also proportional to the applied external field, with all other accelerator parameters held constant. This means that as reconnection occurs the magnetic energy of the CT is converted into kinetic energy of the plasma's forward motion.Lastly, the toroidal component BT is affected in an unusual way by the reconnection process. During reconnection, the BT component of the CT advances into the external field, ahead of the region where Bz is localized, which is normally considered to be the front edge of the CT. This effect can be understood if the 3D nature of the reconnection is taken into account. Since it is the poloidal components of the CT and external field that are undergoing reconnection, the toroidal component of the CT field (and the associated poloidal current density) is unconstrained in the reconnection

zone and can freely expand into the region ahead of the CT. bringing some diffuse plasma with it.Framing camera data. Observe diminishment of light from in front of center conductor This effect has been studied using a fast framing camera that can take a sequence of 12 images of the CT during the interaction. The images can be taken at rate of one frame every 2 ms or at one frame every 0.25 ms. Using these images, the spatial and temporal dependence of light emission intensity of the CT during the interaction is compared to its emission intensity without the external field. Two very distinct effects are observed in this comparison which shed light on the physics of both compression and reconnection effects. Conclusions based on the framing camera data are consistent with the data taken on the same set of shots from surface magnetic probes that measure the axial variation and time evolution of the magnetic field throughout the system Compression Magnetic field data. Increase in Peak Bz field as CT enters Axial field. Time of flight shows dramatic decrease in rate of acceleration (a=0)Interferometer data. Observe compression effect in increased line averaged electron density measured at z= 142 cm position. Density increase by a factor of 1.5 for BAF = 400 Gauss Framing camera data: Observed increase of light emission from trailing plasma located in the accelerator section. This implies that trailing plasma is prevented from getting past the compression interaction region. Each coil can be individually connected or disconnected from the circuit to produce a variety of field geometries.comparison of reconstructed axial dependence of B field signals